Purpose-Built UAVs for Physical Sampling of Trace Contamination at the Portsmouth Gaseous Diffusion Plant – 17331

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ABSTRACT
The sampling of trace amounts of contamination, particularly of low-energy byproducts such as americium, presents a challenge for non-contact sensing. In many cases, such as determining the need for cleaning inside the exhaust shaft of the Waste Isolation Pilot Plant or sampling the walls of the enormous Gaseous Diffusion Plant at Portsmouth, it may be desirable to take physical swab samples at carefully distributed sample locations for analysis by mass spectrometry. Because of the danger posed to human workers in such scenarios, including risk of falls from lethal heights and exposure to low levels of radiation and the hassle of donning and doffing PPE, a low-cost robotic solution is desired. The inaccessibility of the heights involved suggest Unmanned Aerial Vehicle (UAV) solutions, rather than Unmanned Ground Vehicle (UGV) solutions, but conventional quadrotor UAVs are ill-suited to precise physical interaction with their surroundings. Quadrotors are under-actuated, rendering them non-holonomic and preventing the dexterous application of arbitrary generalized force/torques in interaction with the environment.

At Purdue University, the authors have developed a number of novel UAV platforms suitable for dexterous interaction with the environment, making them ideal for such applications. These platforms can independently control forces in all directions, allowing for controlled application of the swab to the surface.

Because of the scale of these structures (over 2 km in the case of the Gaseous Diffusion Plant), flight efficiency is of supreme importance. The Purdue team is took a variety of vehicles to the Gaseous Diffusion Plant for field trials on site in August, 2016. (With results available prior to the meeting.) The Purdue Dexterous Hexrotor is a fully-actuated Hexrotor capable of exerting forces in all six directions of force and torque. Operating alone or in swarms, the Dexterous Hexrotor can fly in free space, transition to contact through impact control, and sample the surface through force control. The Purdue I-BoomCopter is a tricopter with an extra horizontal propeller that enables long-distance flight without pitching and the ability to apply closed-loop forces horizontally. Finally, the Purdue Tiltrotor VTOL is an under-actuated hybrid UAV that combines tilting rotors for vertical takeoff and landing, with a fixed-wing, flying-body design that is ultra-efficient for long-distance flight.

The Dexterous Hexrotor provided two demonstrations of physical sampling of walls and crane rails. In sampling the large open sections of the inside of the plant, a small swarm of three UAVs is commanded to sample three distinct points on an internal map of the building. Human-supervised autonomy permits the UAVs to take off by themselves, find a clear elevation at which to fly through uncluttered space, navigate to their designated sampling points, and pause for confirmation by the

human supervisor. The supervisor is presented with a video image of the intended sampling spot, which, if confirmed, the UAV will automatically approach and sample. The UAVs then autonomously return to the take-off spot.

The second demo involved a single UAV searching upwards, then transitioning into 3-D SLAM mode to wait for a safe sampling spot on the 3-D scan to acquire the sample from the crane rail. The human supervisor, in this case, is responsible for ensuring the absence of cables and other obstacles.

I-BoomCopter demonstrated its high-speed, long-distance coverage ability by making a few fast passes before homing in on a mock-up electrical panel with door, which it opened and closed. The dexterity of the I-BoomCopter results from its large propellers, which allow for controlled hovering and the horizontal thruster for applying forces of significant magnitude.

Finally, the Tiltrotor VTOL is highly efficient in fixed-wing mode, but the tiltrotor is under-actuated in hover. The tiltrotor will take off vertically, then transition to high-speed, long-distance flight to make a number of passes inside the facility.

The significance of these demos is the low-cost implementation of physical sampling over prescribable locations in difficult-to-reach areas of potentially contaminate facilities. To make this tractable over very large facilities, the demonstration of combinations of dexterous hovering ability and long-distance/high-speed flight is also in evidence.

INTRODUCTION

Nuclear power is one of the large scale energy producing technology. United States is the world's largest electricity generator using nuclear energy with 104 reactors. The challenge with nuclear power is the radioactive wastes it generates. Nuclear fuels remain radioactive for thousands of years even after the usage. Safe methods for disposal of the radioactive wastes are technically proven, and geologic repository sites are identified for this purpose.

These repositories or nuclear facilities need regular maintenance. High-consequence materials need inspection time to time, it involves greater risk in handling them. The Waste isolation pilot plant (WIPP) [1], one of the few repositories in United States, was shut down in February 2014 due to leak of radioactive materials. The Portsmouth gaseous diffusion plant that was used for production of enriched uranium for U.S. nuclear weapons program. The plant is in shutdown in 2010 and is preparing for decontamination and decommissioning since 2011. Inspection of the contaminations and leaks in such facilities requires preparation time and risk to humans in handling materials. We need robotic tools to handle and inspect, working in collaboration with workers. Using robots reduce the risk of getting effected by radioactive materials, reduces the time involved in preparation and safety.

In February 2014, the Waste Isolation Pilot Plant (WIPP), a storage facility for high-level nuclear waste located deep underground, two incidents took place. Chemically-induced energetic incident occurred within one of its storage containers that resulted in the release of a small amount of radioactive material. Since then DOE has performed clean ups inside the facility to remove the traces from the walls, ceiling and floor inside the mine. A ventilation system has been arranged for habitation underground, which exchanges air with the surface and a single exhaust shaft leads from the mine to a large bank of HEPA filters at the surface. With nearly 660 meters (2150 feet) long and 4.3 meters (14 feet) in diameter, this exhaust shaft remains a greatest technical challenge in this cleanup program as in fig. 1.

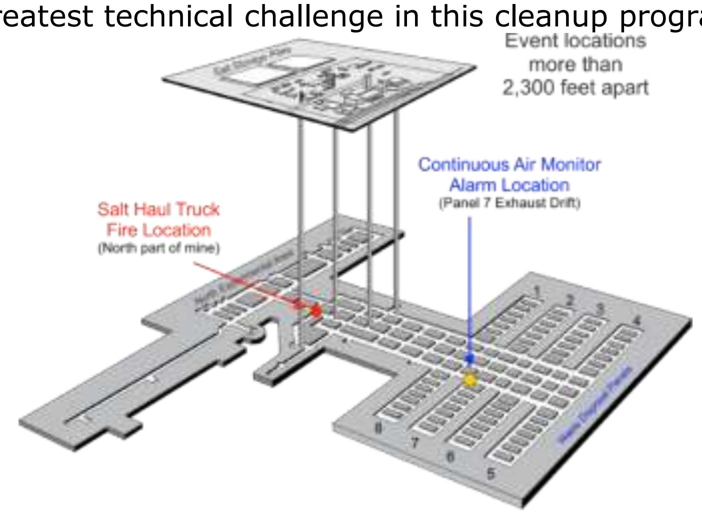


Fig. 1. Spatial layout of the U.S. DOE WIPP site indicating surface buildings with four shafts connecting the main work surface 660 meters below ground. (reprinted from www.wipp.energy.gov)

Robots are well suited for this kind of cleanup program, where it is difficult for humans to reach. The inspection and cleanup required the robot to physically interact with the surface of the shaft. This is because the quantities and energy levels of some materials is very low to detect with non-contact sensing. The shaft also provides an additional challenge to overcome the turbulence, as it is a cylindrical shaft. In this paper, we present the robots that can be used in this kind of scenarios.

The Decontamination & Decommissioning (D&D) [2] Program at the Portsmouth Site needs demolition and disposal of approximately 415 facilities (including buildings, utilities, systems, ponds and infrastructure units). This includes the three Gaseous Diffusion Process buildings. These buildings housed the process equipment and span the size of 158 football fields. These building comprises of cold zones and hot zones, depending the presence of radioactive materials. Cold zones can be accessed by the workers under strict safety rules. Robots becomes the alternative for the workers to inspect and cleanup the facilities. The use of robotic technologies not only increases efficiency, but reduce personnel exposure to hazards.

DOE, office of Environmental management and it Portsmouth/Paducah project office (PPPO) hosted "EM Science of safety: Robotics Challenge" Aug 22-25, 2016. This challenge invited roboticists all around the country to give a demo with the robots and tools assisting the workers in cleanup and inspection activities remotely. In this paper, we present three Unmanned Ariel Vehicle (UAV) robots which we demonstrated in the Robotics Challenge. The UAVs are Dexterous Hexrotor, Boom copter, VTOL (Vertical Take-off and Landing), with unique functionalities and work in swarm behavior to accomplish the tasks. The fig. 2 shows the picture of our team from Purdue University.

Fig. 2. UAV Robotics team from Purdue University.

We will first discuss about each UAV in the next sections and also provide the information on the site visits. Later, in the discussion section, we will talk about the collaboration of the UAVs in a swarm behavior.

DEXTEROUS HEXROTOR

Common UAVs, quadrotors (Drones) in particular, need to tilt their entire body and point their thrust in a particular direction to gain the acceleration. This type of UAV is under-actuated for their six degrees of freedom (DoF) mobility in 3-D space. This is because most quadrotors have four fixed pitch propellers with parallel (and vertical) thrust vectors [3]. The standard quadrotor provides linear force along Z, and torques around X, Y and Z axes. Torque around Z is achieved indirectly through Coriolis forces resulting from differential angular velocities of the counter-rotating propellers. But it can’t exert linear forces directly along X and Y axes. This locomotion is nonholonomic.

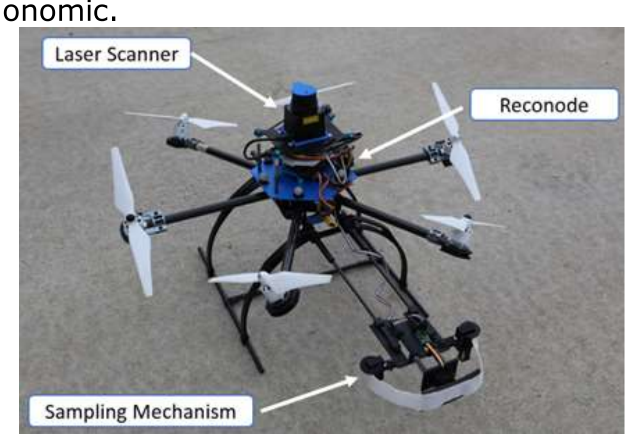


Fig. 3. Dexterous Hexrotor prototype with 30^0 cant angle.

In a nuclear facility, we have harsh environments, no proper lighting, and interaction with the physical environment is necessary. For this purpose, the UAV needs have full control over 6 DoF and should be able to exert forces independently. To explore all six DoF in 6-D Cartesian force space, a new actuation design with nonparallel thrusters has been developed. At Collaborative robotics lab, we developed Dexterous Hexrotor, a fully-actuated UAV platform with nonparallel actuation mechanism, as in fig. 3. The nonparallel actuation is achieved by tilt rotor design, in which the rotor is rotated with respect to their frame at a fixed angle called *cant* angle [4]. This allows the UAV to explore all 6 DoF in three-dimensional space and is a more stable platform. Desired acceleration can be achieved by simply changing the thrust magnitudes of different rotors. This results in faster response to acceleration, with more keeping precise position in the plane [5].

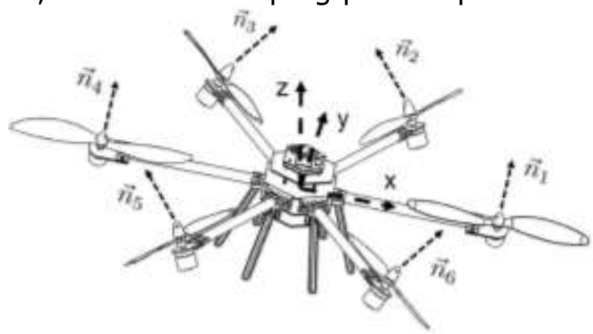


Fig. 4. Configuration of Dexterous Hexrotor, n_i is orientation vector of each rotor's thrust.

The configuration of Dexterous Hexrotor shown in the fig. 4, is designed to have a $\alpha = 30^0$, *cant* angle [6]. The vector n_i is the thrust vector of each rotor, pointing in a nonparallel fashion. Adjacent rotors are rotated in opposite direction of *cant*, to maintain a symmetric basis of vectors. x_i is the positon vector and n_i is the orientation vector of each rotor. Each rotor generated an aerodynamic force with a thrust **f** along the rotor axis and a drag **q** around the rotor axis. The steady-state thrust and the drag by the rotor in free air are modeled as,

$$\boldsymbol{f}_i = C_f \omega_i^2 \boldsymbol{n_i},\ i = 1,2,..,n$$

$$\boldsymbol{q_i} = \begin{cases} C_q \omega_i^2 \boldsymbol{n_i} & if\ i = 1,3,.. \\ -C_q \omega_i^2 \boldsymbol{n_i} & if\ i = 2,4,\ldots \end{cases}$$

Where C_f C_q are motor thrust/torque constants which are determined by static thrust tests, ω_i is rotor speed and n is the number of rotors. The generalized net force and torque,

$$\boldsymbol{f} = \left[f_x\ f_y\ f_z\right]^T = \sum_{i=1}^{n} f_{\boldsymbol{i}}$$

$$\boldsymbol{\tau} = \left[\boldsymbol{\tau}_x\ \boldsymbol{\tau}_y\ \boldsymbol{\tau}_z\right]^T = \sum_{i=1}^{n} x_i \times \boldsymbol{f}_i + \boldsymbol{q}_i$$

$$\binom{\boldsymbol{f}}{\boldsymbol{\tau}} = M_\alpha \cdot \omega^2$$

In the equation 5, general mapping matrix M_{α}, maps the square of rotor speed to generalized force/torque. Where $\boldsymbol{\omega} = [\omega_1\ \omega_2, \dots, \omega_n]^T$ is the rotor vector with *n* number of rotors. The $rank(M_{\alpha}) = 6$, shows that the UAV has independent control over 6 DoF [7]. For a fully actuated platform, Dexterous Hexrotor, the orientation and position control are separate. An attitude controller is used to stabilize the Dexterous Hexrotor for orientation and also for human controlled flight. This allows the Dexterous Hexrotor to mode without tilting and tilt without moving. This feature give advantage while interacting with the physical environment.

Navigation controller is used to control the position of the Dexterous Hexrotor. The attitude is measured by a 9 DoF IMU sensor. We use Simultaneous Localization and Mapping (SLAM) techniques provided by Robot Operating System (ROS), to develop maps inside a facility, localize in the map and path planning. Hokuyo laser sensor is used for the SLAM. For outdoor application, we employed a GPS sensor to measure the position in space and a barometer.

Real-time Applications

To inspect the exhaust shaft of the WIPP, as described in the introduction, we propose to employ our fully autonomous Dexterous Hexrotor for inspection and cleaning the surface of the inside walls if shaft. The Robotic inspection and cleanup required physical interaction with the surface of shaft. The shaft is circular in cross section, which introduces turbulence due too aerodynamic effects. Dexterous is a best suit for such applications. The nonparallel actuator mechanism allows us to fight the turbulence and keep the platform stable. It can also interact with the surface for inspection and cleanup. A rigid arm mounted onto the platform as show in the fig. 5, which will carry a sampling mechanism at the end.

Fig. 5. Force Controlled Interaction with environment at silo.

To interact with the surfaces, a hybrid controller is implemented to perform force control in one DoF and stabilize other five DoFs. The controller consists of position/velocity controller, impact controller and force controller. PID controller is used to stabilize UAV attitude and control position/velocity. A proportion controller with negative gain and force feedforward is used to control the impact. Then it transits to proportion force controller with force feedforward after the impact. Fig. 6

shows the hybrid control strategy, which will be switching between the controllers depending on the required flight control.

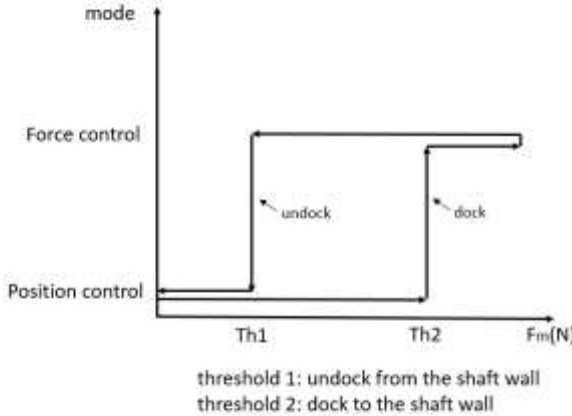


Fig. 6. Hybrid Control strategy for Flight.

The DOE's Robotic challenge held at Portsmouth gaseous diffusion plant required inspection and cleanup for Decontamination and Decommissioning. Dexterous Hexrotor was proposed for interaction with the surfaces and collect the samples. This platform also employs the similar control strategy with the rigid arm for interaction. Inside a facility at the Portsmouth site, we demonstrated swabbing of a crane rail. The pictures in the fig. 7 are taken by the on board camera. We can see the Dexterous Hexrotor approaching the crane rails located overhead. In the second picture the rigid arm mounted onto the Dexterous Hexrotor makes contact with the surface of the rail to gather samplings. The samples are then collected at the ground station for further processing of radioactive materials. At the end, the arm is wiped with a cleaning solution to prevent contamination.

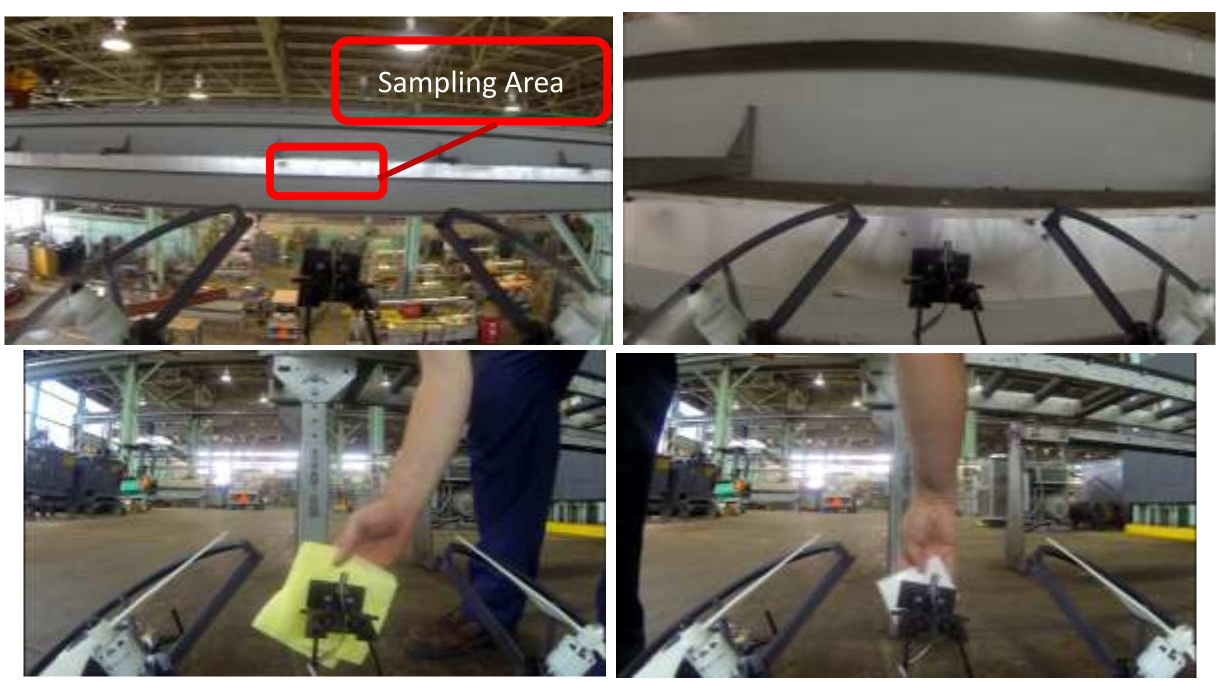


Fig. 7. Demo of collecting samples with Dexterous hexrotor inside one of the Protsmouth facilities.

I-BOOMCOPTER

The Interacting BoomCopter (I-BoomCopter) is custom designed for enhanced physical interactions with the environment [8]. The vehicle is based on a Y-shaped tricopter frame with an additional boom mounted in the front of the vehicle. A mechanism, referred to as the boom-prop, is mounted on this front boom that allows a fourth propeller to rotate around the boom. It has been designed with symmetric propeller blades as in fig. 8. Therefore, by rotating either clockwise or counter-clockwise, it can provide thrusts in the vehicle's forward or reverse direction (perpendicular to the main rotors' thrust). Thus, the boom-prop, along with end-effectors attached at the end of the front boom, enable the I-BoomCopter to apply horizontal forces while in a stable hovering configuration, making the I-BoomCopter well suited for performing aerial manipulation tasks.

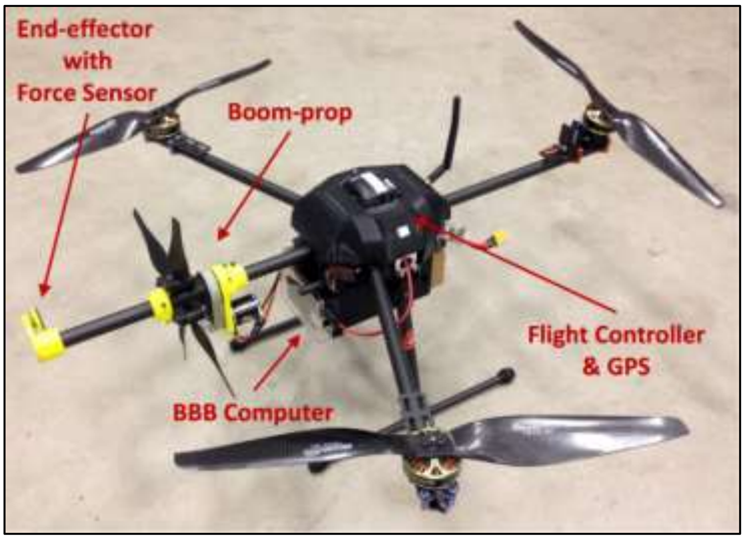


Fig. 8. The Interacting BoomCopter

The I-BoomCopter's airframe, motors, propellers, and power source were each selected to increase its payload capacity and overall efficiency. Its large 15-inch diameter, carbon fiber propellers and 4-cell lithium polymer batteries give the I-BoomCopter a flight time of 21+ minutes and a maximum payload of 1.86 kg. The vehicle also carries a BeagleBone Black (BBB) computer (running Linux and the Robot Operating System (ROS)), which is capable of performing on-board, real-time image processing, in addition to collecting and analyzing sensor data. Thus, the I-BoomCopter can implement vision-based, closed-loop control systems to perform intelligent physical interactions with the environment.

Dynamic Model

The mathematical model of the I-BoomCopter consists of a body coordinate frame (x_b, y_b, z_b) that moves along with the UAV (B-frame), and an inertial coordinate frame (x, y, z), which is the fixed reference frame of the earth (E-frame). Both of the coordinate frames are right handed coordinate systems as shown in the Fig. 9 above. The roll (ϕ), pitch (θ) and yaw (ψ) angles are measured relative to the inertial frame as right handed rotations around the positive x, y and z axes, respectively. The overall mathematical model is given by the following equations.

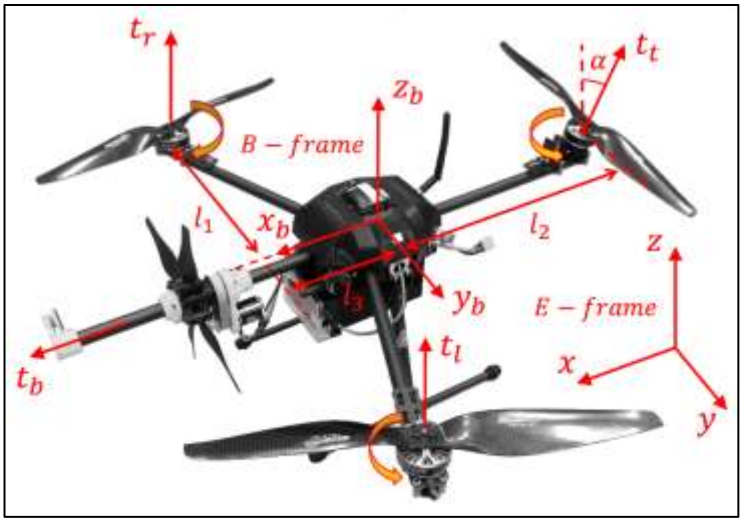


Fig. 9. Free-body diagram of I-BoomCopter.

$$\dot{X} = V$$
$$\dot{\Theta} = W_{xyz}\Omega$$
$$\dot{V} = \frac{1}{m}R_{xyz}F_b + G$$
$$\dot{\Omega} = I^{-1}(T_b\Omega \times I\Omega)$$

Here, $X = [x, y, z]^T$, $V = [\dot{x}, \dot{y}, \dot{z}]^T$, and $\Theta = [\phi, \theta, \psi]^T$ are the vehicle's position, velocity and orientation represented in the inertial frame. $\Omega = [p, q, r]^T$is the vector of angular velocities about the x_b, y_b and z_b axes, respectively, relative to the body frame. W_{xyz} and R_{xyz} are the transformation and rotation matrices for the conversion of vectors from the body to the inertial frame. m is the mass of the I-BoomCopter and $G = [0,0, g]^T$ denotes the gravity vector (g is the gravitational acceleration). $F_b = [F_{xb}, 0, F_{zb}]^T$ and $T_b = [\tau_{xb}, \tau_{yb}, \tau_{zb}]^T$ are the forces and torques in the system, expressed in the body frame. F_{xb} equals the boom-prop thrust when the boom-prop is engaged and is zero when the vehicle is only hovering. I is a 3x3 diagonal inertia matrix with I_{xx}, I_{yy} and I_{zz} as its diagonal elements; these values represent the moments of inertia along the x_b, y_b and z_b axes, respectively. A more detailed description of the force, torque, transformation and rotation matrices can be found in [8]. The dynamic model is important for the implementation of model-based control schemes and for simulating the vehicle behavior and performance in a number of different scenarios.

DOE site visit - Portsmouth

As described in the Abstract, we performed an indoor flight and an electrical enclosure door manipulation task with the I-BoomCopter as part of a demo for the DOE at the Portsmouth Gaseous Diffusion Plant (see Fig. 10). During the flight, the boom-prop was engaged to demonstrate the I-BoomCopter's ability to move forward at high speeds without the need to pitch the vehicle forward. In addition, the I-BoomCopter's carefully tuned flight control parameters and standardized radio control system made it possible for some of the union workers present at the demonstration to teleoperate the system. The electrical enclosure door manipulation task required the I-BoomCopter to detect an electrical enclosure, move into position to pull on the enclosure door's L-shaped handle, and then open and close the door. We demonstrated this task with the vehicle moving on the ground (see Fig. 10 for set up details), to focus the demonstration on the physical interaction element of the task, but work is continuing to perform this task autonomously during flight. We approached this task with an emphasis on simplicity and efficiency, since the vehicle may need to perform dozens of these manipulations during a single mission, and any energy saved by using lighter-weight components that consume less electrical power, can save time and money by extending the reach of each mission.

Fig. 10. I-BoomCopter Demo at a Portsmouth facility. Hovering and Opening enclosure door (fitted with swivel casters and a tail fan to enable smooth motion on the ground).

The door-opening and closing task is comprised of two key elements: 1) image processing to visually locate and approach the electrical enclosure, and 2) physical manipulation of the door through the use of the boom-prop actuator. The image processing was achieved through the use of a single on-board webcam and the BBB computer. The image processing algorithm has three main stages: first, detecting the enclosure door and computing its centroid (marked respectively on the video feed with a red rectangular outline and a yellow dot), second, detecting the door handle and computing its centroid (marked respectively with a blue outline and yellow dot on the video feed), and third, checking whether or not the end-effector has hooked onto the handle (indicated on the video feed by outlining the handle in green when not hooked, and outlining the handle and end-effector with a cyan rectangle when hooked). To illustrate these stages of image processing during the demonstration for the DOE, the vehicle was placed in a starting position about three feet from the electrical enclosure, and moved by hand toward the door while the on-board video feed was displayed remotely on a laptop.

Once the end-effector was hooked on the electrical enclosure door handle, an RC-transmitter was used to activate the boom-prop and pull the door open. After the door was opened, the RC transmitter was used to activate the boom-prop in the reverse direction, and thus close the door. An additional propeller (referred to as the tail fan) was attached on the tail boom to apply horizontal forces at the end of the tail boom and thus provide yaw control while the vehicle is on the ground (since yaw control during flight is obtained by rotating the main tail rotor, to convert some of its upward thrust to horizontal thrust, and thus rotate the vehicle). This tail fan was manually operated simultaneously with the boom-prop via the RC-transmitter to keep the I-BoomCopter oriented so its hook end-effector was normal to the enclosure door throughout the opening and closing operations. Subsequent work after the DOE demo has achieved both autonomous door opening [8] and closing. This utilized the vision-based control algorithm presented here along with force-feedback from dual force sensors embedded into the end-effector.

TILT-ROTOR VTOL

Most commercial UAVs available on the market are quadrotors. They have the advantage of low cost, high maneuverability and user friendly design. However, their design is limited by their endurance. Most of the designs on the market has endurance limited to 30 minutes. Unless a revolutionary new design on battery technology emerges, the endurance of quadrotors is unlike to be improved.

An improved design is to combine the idea of fixed-wing aircraft and multirotor. Such design can maintain the maneuverability of quadrotors and gain efficiency of fixed-wing aircraft. An example is the amazon prime air: it uses one rotor to provide horizontal thrust and eight rotors to provide vertical thrust during the takeoff and landing. It can carry up to 5 pounds' cargo to a range up to 10 miles [9]. However, it requires 8 motors to provide vertical thrust only during takeoff and landing. This wastes not only payload mass but also cost extra maintenance requirement. Therefore, developing a UAV with rotors that are utilized both in take-off and forward flight reduces the actuators weight.

Prototype

The UAV is comprised of pair of semi-wings, with at least two rotors mounted in the wing. Rotors can rotate relative to the first axis and tilt relative to the second axis. It has two modes: vertical take-off and landing mode, where UAV applies thrust in vertical direction to lift off and land. In this mode it operates same as multirotor and can hover after takeoff. After first mode, UAV transitions to second mode where the thrust is applied in horizontal direction. During the transition rotors start to tilt forward at the same time and change from vertical position to horizontal gradually. After the transition is complete, UAV operates as fixed wing UAV with two motors for forward flight. UAV also comprises at least two through openings within which rotor may tilt to change to airplane mode.

As shown in fig. 11, two tilt-able motors (2) are individually installed on each semi-wing (1). Two servos (7) in the lower surface of the wings provide torque required to tilt the rotational motors which are mounted on support rod (3). Rod (8) connects servo with horn (9) that pushes the rod (3) to tilt the motor. Two similar servos (10) which also located in the lower surface of the wings control the elevens (4) on the trailing edge on the wing. Control horn (12) is used to move elevens by servo. Propellers (6) are mounted to the motors.

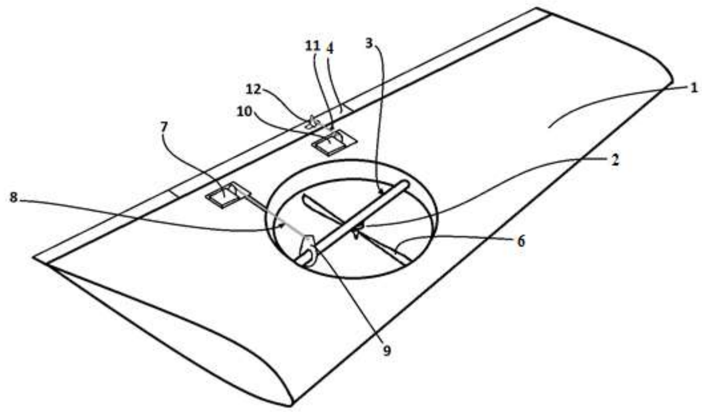


Fig. 11. Design of one wing and components embedded to it.

Arduino Due is used as a flight controller for this UAV. Angle, angle rate, and orientation updates are obtained from 9DOF IMU which consist of accelerometer, gyroscope, and magnetometer [10]. Rotors are controlled through electronic speed controllers (ESC) which receive command from flight controller. Tilting of rotors are done with servos. UAV can be manually controlled by pilot by sending signal from transmitter to 2.4 GHz receiver.

Dynamic model

Let $B = \{X, Y, Z\}$ be the body fixed frame of the aircraft. Force lines (T_1, T_2) are tilted by angles β_1 and β_2 respectively from body axis Z as shown in fig. 12.

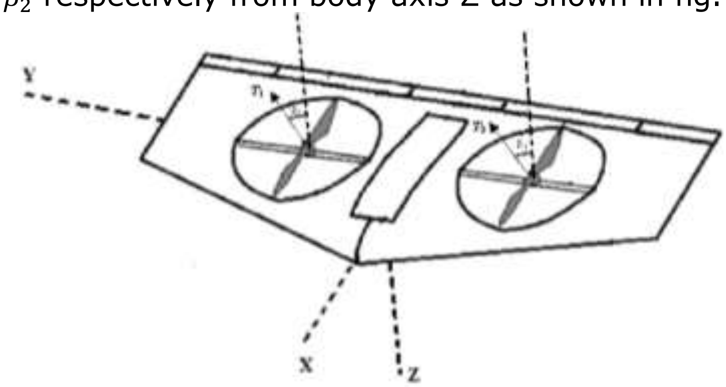
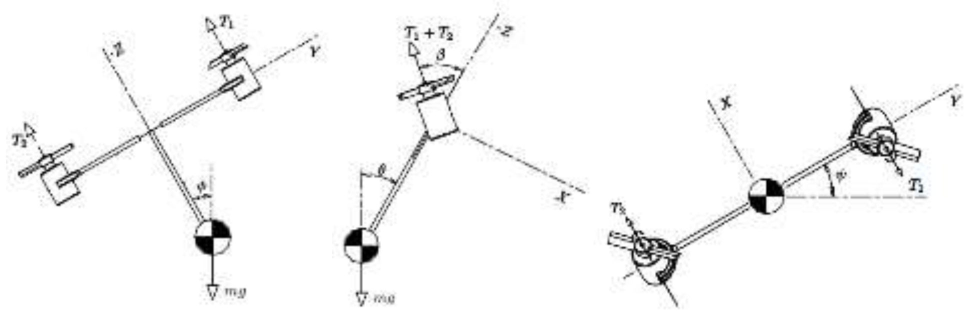


Fig. 12. Picture shows the body axes of the UAV and tilt angles β_1 and β_2

Bi-rotor configuration controls roll, pitch, and yaw in hover by tilting rotors and difference in speed of rotors. Altitude is controlled by increasing or decreasing thrust of both rotors at the same time.

Roll:
Roll motion is controlled by difference in thrust in rotors (see Fig . 13a). When speed of one rotor becomes greater than other, UAV starts to rotate around X axis.
Pitch:
Pitch is controlled by torque that comes from thrust and distance between center of gravity (c.g.) and force line. Tilting the rotors at the same direction changes the distance between the force line and c.g. increasing or decreasing the torque magnitude (see Fig. 13b). This gives rotation around Y axis.

Yaw:
Yaw motion of UAV is controlled by tilting the rotors in the opposite direction (see Fig. 13c). Having the same thrust from both rotors, when one of the rotor tilts and has positive β angle, and the other one tilts and has negative β angle, UAV starts rotating around Z axis.



(a) Roll motion (b) Pitch motion (c) Yaw motion

Fig. 13. Representation in 2D plane and shows the angles they affect with respect to inertial frame.

In order to maintain the stable hovering UAV uses PD controller. Pitch and Roll have controller on angles and controller on angular rate. Elevator and aileron commands on transmitter corresponds to angles and range from -180 degrees to 180 degrees. Yaw has angular rate controller. Rudder command corresponds to change in angle. This way, when UAV needs to yaw left or right, after turning it by command from transmitter, it won't return to the initial orientation when stick moves to middle in transmitter.

During the DOE site visit, Tilt-rotor VTOL UAV was presented along with Dexterous Hexrotor and I-BoomCopter from Purdue University. The main goal of Tilt-rotor VTOL UAV is to transport other mission specific UAVs to their mission sites. It's build to have a capability of vertical takeoff in order to be able to lift off in restricted space and have fixed wing to increase flight endurance. During missions such as sampling nuclear waste tunnels, it could deliver the UAVs such as Dexterous Hexrotor close to their mission sites so that they don't consume their energy on flight, but focus on the mission since the battery cannot last for a long time.

DISCUSSION
Nuclear facilities usually consist of huge facilities, they span over a mile on the surface of the earth as in the Portsmouth site and long shafts reaching the underground facilities as in WIPP. Whatever the size of the facility is, need for robots to perform inspection spanning the entire building. We at Purdue University are collaborating with different departments to solve this problem. Demonstrated a combinations of dexterous hovering ability, interaction with the environment and long-distance/high-speed flight. In order to perform inspection tasks, the robot should be about to cover long distances and also physically interact with the surfaces for collecting samples. We proposed a swarm of UAV that can accomplish the above mentioned tasks.

This paper presented three different types of UAVs which has unique capabilities. These capabilities put together. When we talk about UAVs, there is always an issue with the flight time. This is because all the UAVs doesn't last longer flights, due to their limited payload capability for battery pack. The structures, like the gaseous diffusion plant, requires higher flight efficiency. The Dexterous Hexrotor, capable exerting forces independently in all six directions of force and torque, is used mainly for interacting with the walls and surfaces to collect samples. Next, we presented the I-BoomCopter, with a horizontal propeller which enables long-distance flights more efficient. It can also exert closed-loop forces horizontally as described in a door opening scenario. Both the UAVs are not designed to last longer to cover the entire distance of the building. For locomotion through longer distances, VTOL is presented. Fixed-wing, flying-body design that is design to travel long distances efficiently.

The three UAVs are expected to work as a team. The Dexterous Hexrotor and I-BoomCopter are mainly used for interaction with the walls and surfaces. VTOL is employed to carry these platforms to a longer distances and deploy them for their tasks. The UAVs doesn't need to collectively work all the time. For a certain task, like opening an electric box and apply sealant inside it. Here we would need the I-BoomCopter to open the electric box, similar to that of the Portsmouth site demo, and the Dexterous Hexrotor would apply the sealant. There are situations where we need lot of samples to be collected in less time, then we need whole bunch of Dexterous Hexrotor to work in a swarm, and collect samples simultaneously.

The purpose of these UAVs is to assist the worker in performing their duties safer and efficiently. During the Portsmouth visit, the workers were excited to pilot the UAVs. This makes their work place more interesting and motivating. The overhead rail at the Portsmouth site (mentioned in the Dexterous Hexrotor section) was not explored for several months, as it is difficult to reach for the workers. The workers needed orders from higher authorities for safety, in order to access the rail. But, Dexterous Hexrotor could collect the samples from the rail, within few minutes. Use of robot reduced the preparation time, for the workers to access the rail, from several months to few minutes. This is a live example of how efficient the robots can assist the workers efficiently and safely.

CONCLUSION

This paper presents novel models of UAVs to assist workers in a nuclear facility. DOE performs operations to detect radioactive materials and clean them for contamination at locations like WIPP, Portsmouth gaseous diffusion plants, etc. Sampling of the contamination of low-energy byproducts such as americium poses a greater challenge to detect with non-contact sensing. There is a need for inspection and cleanup of the trace amounts. It is not safe for the workers to enter the facilities and perform the tasks. The workers may get exposed to radiation, risk of accessing great heights and the preparation time involved in it are the major setbacks to accomplish these tasks. We proposed low-cost robotic solution for these tasks. The robots are meant to work along with the workers making the work safer and efficient. We presented the Dexterous Hexrotor, I-BoomCopter and VTOL for different applications. Dexterous Hexrotor operating alone or in swarms, assist the workers in collecting the sample from the walls and other surfaces and also apply sealants. I-BoomCopter is presented for its efficient long-distance coverage and also apply closed-loop forces horizontally for small door opening. Third UAV, Tiltrotor VTOL, is highly efficient in covering longer distances at higher speeds. In the last we discussed the significance of using the UAVs collectively to accomplish the tasks. The workers are always excited and motivated to use robots in their work places. Robots make the work place more interesting and safe.

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